ANAEROBIC CO-DIGESTION OF DELIPIDIZED MICROALGAE BIOMASS AND FOOD RESIDUES

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This paper focuses on some experimental investigations and a mathematical modeling of the anaerobic co-digestion (AcoD) of Chlorella vulgaris *defatted microalgae biomass and food waste (potato waste). Using experimental data for the AcoD of the biomass in mesophilic conditions (37°C) a regression model consisted in four equations was elaborated. Based on this model the AcoD process can be partially simulated and optimized with satisfactory results. This model will be a part of a more extended statistical model that will be very useful for the search of maximization of biogas production.*

Keywords: anaerobic co-digestion, microalgae biomass, food residues, experimental investigation, regression model

1. Introduction

Anaerobic digestion (AD) is an efficient technology for the energetic valorization of various types of biomass (including microalgae biomass), and it is predicted to play a crucial role in the future of renewable energy production [1].
The experimental results of the study on the effects of technical parameters of the AD of the corn- DDGS (distiller's dried grains with solubles) under mesophilic conditions [2] has shown that both pH-control and stirring have a significant influence on the methane production. With respect to the conditions without stirring and without pH-control 41% higher methane production has been observed when applying agitation; a further increase of 24% was observed when applying also pH-control. The results of the fed-batch experiment with partial evacuation of the biomass indicate a clear improvement of the digestion performance parameters, attributable to the acclimation of the anaerobic biomass to the substrate.

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Co-digestion (AcoD) is the simultaneous digestion of a homogenous mixture of two or more substrates.Traditionally, anaerobic digestion was a single substrate, single purpose treatment. Recently, it has been realized that AD as such became more stable when the variety of substrates applied at the same time is increased [3]. AD of a single waste has many universally observed drawbacks, which usually cause the instability of the process. Derived from mono-digestion, co-digestion, thought mixing and treating several organic wastes in single equipment, shows great perspectives [4].

Several possible ecological, technological and economical advantages and limitations of AcoD are shown in Table 1 [3].

Table 1

Merits and limits of AcoD technology

Merits	Limits
Improved nutrient balance and digestion	Increased digester effluent
Equalization of particulate, floating, settling, acidifying, etc.	Additional pre-treatment requirements
Additional biogas collection	Increasing mixing requirements
Possible gate fees for waste	Wastewater treatment requirement
Additional fertilizer (soil conditioner) reclamation	High utilization degree required
Renewable biomass (“Energy crops”) disposable for digestion in agriculture	Decreasing availability and rates
	Hygenization requirements
	Restriction of land use for digestate
	Economically critical dependent on crop and yield

In addition, codigestion offers several possible ecological economical advantages [5].

Recent studies have demonstrated that microalgae biomass is a promising source of co-substrate for AcoD and a lot of studies tried to find the optimum condition for the efficiently convert of microalgae biomass into biogas. The production of biogas from microalgae biomass is mainly determined by the macromolecular composition of microalgae biomass (carbohydrates, proteins and lipids). Also, due to the complex composition of microalgae biomass and to the complexity of the AcoD process is very difficult to establish its optimum parameters [6].

This paper focuses on some experimental investigations and a mathematical modeling of the AcoD of *Chlorella vulgaris* defatted microalgae biomass and food waste (potato waste). Using experimental data for the AcoD of the two types of biomass in mesophilic conditions (37°C) a regression model was elaborated. On the base of this model the optimal conditions for biogas production can be predicted.

2. Experimental

Methods and materials

Fermenter Bioengineering RALF laboratory

Experiments of AcoD of potato waste and residual microalgae biomass were performed in a Bioengineering RALF laboratory fermenter (fig. 1) with a volume of 5 L. The fermenter is equipped with a double shell, 3 peristaltic pumps for feeding or evacuation, a mechanical stirrer (stirring speed up to 1500 rpm), temperature measurement sensor and automated temperature control function, pH sensor and dissolved oxygen measurement sensor.

Fig. 1 Fermenter Bioengineering Ralf laboratory

The temperature regime for the AcoD in mesophilic conditions was in the range 20 - 40 ° C, the temperature in the fermentation vessel being set at 37 ° C. The digestate pH value was 7.70. For environmental homogeneity, a variable agitation regime was chosen from 0-40 rpm. The resulting gas is collected in special gas collection bags connected to the gas outlet.

Biogas analyzer - Biogas 5000

The composition of the biogas obtained from the AcoD process was established using a Biogas-5000 portable biogas analyzer equipped with sensors for:

- CH_4: infrared measurement in the volume range 0 – 100%;
- CO_2: infrared measurement in the volume range 0 – 100%;
- O_2: electrochemical sensor in the volume range 0 – 25%;

- H_2S: electrochemical sensor in the range 0 -5000 ppm.

Determination of biogas volume

The volume of gas resulting from the digester was determined daily by the method of liquid displaced by gas (fig. 2): a graduated cylinder filled with water – and turned back was connected to the biogas source. After half an hour the volume of liquid displaced by the gas was read. The resulting volume of gas is equal to the volume of displaced liquid.

Fig. 2 Determination of biogas volume

Materials

As a substrate for the study, microalgal biomass was used, respectively microalgal biomass obtained after extraction of lipids by ultrasound assisted extraction mixed with potato waste.

Experimental data

For the purpose of mathematical modeling of the anaerobic co-digestion process of potato waste mixed with microalgae biomass, the following independent variables were selected in relation to the measurement and use possibilities as control parameters of the process:

- Fermentation time (days) - the process was followed daily for at least 6 days;
- The ratio waste (potato waste): microalgae biomass - 1: 1; 2: 1; 3: 1
- Amount of feed biomass (g / day) - 50; 100; 150 g

For these independent variables were experimentally determined as dependent variables: volume of biogas (mL / h) and biogas composition.

The corresponding experimental data are presented in Table 2 and Table 3.

Table 2

Volume and biogas composition function of time and waste:microalgae biomass ratio

Day	Waste : microalgae biomass 1:1					Waste : microalgae biomass 2:1					Waste : microalgae biomass 3 : 1				
	Vol. mL/h	Biogas composition				Vol. mL/h	Biogas composition				Vol. mL/h	Biogas composition			
		% CH_4	% CO_2	% O_2	ppm H_2S		% CH_4	% CO_2	% O_2	ppm H_2S		% CH_4	% CO_2	% O_2	ppm H_2S
1	22,3	58,21	39,78	2,34	66	19	49,4	41,4	3,40	169	21	48,2	45,4	2,40	169
2	20,5	56,7	39,4	3,40	169	18	52,7	45,4	1,30	134	19	49,7	45,4	2,68	134
3	17,3	53,6	44,4	1,30	134	21	49,3	49,2	1,50	209	20,5	47,3	51,2	1,20	209
4	19	59,3	36,2	2,70	209	19	50,8	47,5	1,70	354	17	45,3	49,5	1,87	354
5	20	58,8	37,5	2,70	354	21	49,1	46,2	1,20	366	17	50,1	48,2	1,40	366
6	22	59,7	36,3	2,20	366	20	50,7	44,75	1,78	80	18	47,66	48,3	2,17	78

Table 3

Volume and biogas composition function of time and amount of feed biomass for waste:microalgae biomass ratio 1:1

Day	Feed biomass 50 g/day					Feed biomass 150 g/day					Feed biomass 200 g/day				
	Vol. mL/h	Biogas composition				Vol. mL/h	Biogas composition				Vol. mL/h	Biogas composition			
		% CH_4	% CO_2	% O_2	ppm H_2S		% CH_4	% CO_2	% O_2	ppm H_2S		% CH_4	% CO_2	% O_2	ppm H_2S
1	22,5	59	36,5	1,6	197	21,5	44,8	46,9	3,7	88	40,5	45,5	45,4	3,1	66
2	21,5	55,7	37,2	3,1	6	20,5	45,3	47,5	2,3	556	45	46,1	46,3	4,8	382
3	25	45,1	46,6	4,9	3	36	49,8	49,8	1,7	1136	49	48,9	45	1,3	1784
4	27,5	61,2	36,2	1,9	145	34	44,8	47,8	2,6	828	45	42	47,7	5,2	643
5	17,5	52,4	31,9	1,5	6	39	49	48,1	1,2	1221	35	44,3	48,1	1,8	830
6	16,5	57,7	35	7,3	4	32	46,1	45,8	3,4	84	41,5	53,3	40,8	1,4	1491
7	27,5	42	50,2	6,5	10	23	49	42,6	5,8	199	39	42,1	47,6	1,5	1030
8	27	48,2	45,7	3	169	40	50,8	49,9	1,7	1257	42	41,7	47,9	4,2	382
9	25	45,7	42,3	5	9	35	435,5	47,9	2	651	47,5	42,5	47,4	2,2	658

10	27	56,5	38,6	4	43	50	53,7	38,7	2,1	1314	43	53,1	39,1	5,8	1310
11	21,5	56,5	37,9	5,8	58	39	43,5	49,9	2	651					
12	21,5	56,2	37,7	4,2	543	26,5	44,9	43,7	2,8	192					
13	20,5	53,7	39,5	3,4	350	34	55,2	40,5	4,2	665					
14	16	49,4	46,2	4,4	7	38,5	52,2	42,1	1,6	1081					
15	18	45,5	46,2	8,3	116	32	43,6	47,9	3,1	134					
16	19,5	52,2	43,8	2,8	698	24,5	45,4	46,8	1,9	467					
17	17,5	46,8	47,9	2,4	291	34	54,5	37,7	1,3	1067					
18	17	51,1	39	4,3	57	33	46,8	45,5	1,7	710					
19	16	52,3	49,6	3,2	75	35,5	48,5	42,8	1,8	1265					
20	18	50,9	37,3	4,8	46	38	43,3	47,1	1,8	494					
21	23,5	56,6	39	2,9	754	28	45,3	46,1	2,1	493					
21	18,5	54,4	36,6	2,9	122	30,5	54,1	44	1,1	1012					
23	15	50,2	42,8	5	61	25	44,8	47	1,9	563					
24	21	52,2	43,2	2,1	912	34	52	45,6	2,2	619					

3. Mathematical modeling

The available mathematical models for AD and AcoD can be divided into five categories [7]: basic kinetic models, anaerobic digestion model no. 1 (ADM1), statistical models, computational fluid dynamics (CFD) models and other algorithm approaches (such as modeling based on Artificial Neural Networks and Genetic Algorithms [8]).

Apart from main stream mechanistic models focusing on the fundamental characterization of AcoD, statistical models emphasize the interrelationship between key parameters (e.g. substrate/ co-substrate ratio, C/N ratio, organic loading rate, and temperature) and the outputs,(e.g. methane yield and VS reduction) [9]. Statistical models are suitable methods for optimizing methane production from AcoD using a variety of substrates [10]. The standard forms of volume of biogas the statistical models are linear, quadratic, special cubic, full cubic, and special quartic models [11].

In this paper were obtained several statistical models to express the interrelationship between key parameters. Based on the experimental data presented in Table 2 and Table 3, a quantitative description of the fermentation process was followed. The following correlation relations were sought:

1- Volume of biogas = f (Fermentation time, Ratio potato waste: microalgae biomass);

2- CH_4 Concentration = f (Fermentation time, Ratio potato waste: microalgae biomass);

3- Volume of biogas = f (Fermentation time, Amount of feed biomass);

4- CH_4 Concentration = f (Fermentation time, Amount of feed biomass).

4. Results and discussion

Initially, there were tried polynomial correlations using the software *add-on.excel/data analysis*. These have proved to be incorrect regardless of the degree proposed for the polynomial; therefore, correlation with algebraic polynomial equations is not possible for the experimental data in question.

As a result, the use of DataFit 8.1 software by Oakdale Engineering has been approached. This allows for obtaining hundreds of regression equations for a function of up to 20 independent variables. The offered equations are ordered in increasing order of the standard error of estimation.

Regression 1:

$$Y=a+b*\log(x_1)+c*x_2+d*\log(x_1)^2+e*x_2^2+f*\log(x_1)*x_2+g*\log(x_1)^\wedge 3+h*x_2^3+i*\log(x_1)*x_2^\wedge 2+j*\log(x_1)^2*x_2 \quad (1)$$

where: Y = Volume of biogas [mL/h]; x_1 = Fermentation time (days); x_2 = Ratio potato waste: microalgae biomass.

Regression 2:

$$Y=a+b*\log(x_1)+c*x_2+d*\log(x_1)^2+e*x_2^2+f*\log(x_1)*x_2+g*\log(x_1)^\wedge 3+h*x_2^3+i*\log(x_1)*x_2^\wedge 2+j*\log(x_1)^2*x_2 \quad (2)$$

where: Y = CH_4 Concentration [%]; x_1 = Fermentation time (days); x_2 = Ratio potato waste: microalgae biomass.

Regression 3:

$$Y=a+b*\log(x_1)+c*x_2+d*\log(x_1)^2+e*x_2^2+f*\log(x_1)*x_2+g*\log(x_1)^\wedge 3+h*x_2^3+i*\log(x_1)*x_2^\wedge 2+j*\log(x_1)^2*x_2 \quad (3)$$

where: Y = Volume of biogas [mL/h]; x_1 = Fermentation time (days); x_2 = Amount of feed biomass (gr).

Regression 4:

$$Y = a+b*x_1+c*x_1^2+d*x_1^3+e*x_1^4+f*x_1^5+g/x_2+h/x_2^2+i/x_2^3+j/x_2^4+k/x_2^5 \quad (4)$$

where: Y = CH_4 Concentration [%]; x_1 = Fermentation time (days); x_2 = Amount of feed biomass (gr).

Regression coefficients of eqs. (1) – (4) are given in Table 4 and Table 5.

Table 4

Regression coefficients of equations (1) – (2)

Coefficient	Eq. (1)	Eq. (2)
a	131956607093176	993112904964607
b	-9.77647171328324	-4.20558338954884
c	-197934910639729	$-1.48966935744682 \cdot 10^{15}$
d	1.15730056773507	4.97228971337796
e	73309226162861.9	551729391646970
f	4.27324980494113	-0.395339715264388
g	1.87757114248775	-0.72323906078119
h	-7330922616286.17	-55172939164696.9
i	-0.199411259870861	0.210830600592322
j	-1.62171867858004	-0.6741575435518

Table 5

Regression coefficients of equations (3) – (4)

Coefficient	Eq. (3)	Eq. (4)
a	-151452578434962	-36184682263057.9
b	-127.702873182192	5.75282503984513
c	101828376393284	-5.1126109048307
d	-1.71013450350619	1.62493035556112
e	-22696813141644.3	-0.21023488265797
f	61.928357695364	$9.3771404699881 \cdot 10^{-3}$
g	0.115302280829114	$1.42524922002619 \cdot 10^{17}$
h	1677786879542.34	$-3.87871254364431 \cdot 10^{19}$
i	-6.96700668234365	$3.13540768122912 \cdot 10^{21}$
j	-1.00968058356661	$-5.1759903613049 \cdot 10^{22}$
k		$-1.28160639217412 \cdot 10^{24}$

The errors given by eqs. (1) – (4) are indicated in Table 6.

Table 6

Maximum and average relative errors

Equation	Maximum relative error %	Average relative error %
1	10.496	3.34
2	6.248	1.91
3	22.446	12.30
4	20.238	6.22

The correlations given by eqs. (1) and (2) are very good. The correlations given by eqs. (3) and (4) can be considered satisfactory, especially in terms of the average relative error. The system of eqs. (1) – (4) can be used in a limited simulation and optimization of this AcoD process.

The 3D representation of eqs. (1) – (4) are presented in Figs. 3 – 6.

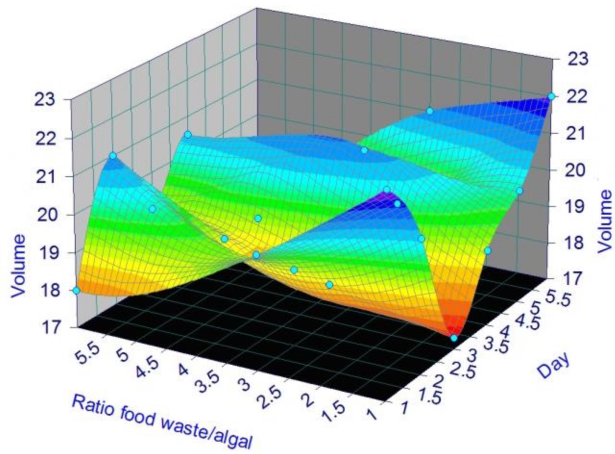
Volume
Ratio food waste/algal
Day
23
22
21
20
19
18
17
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1

Fig. 3

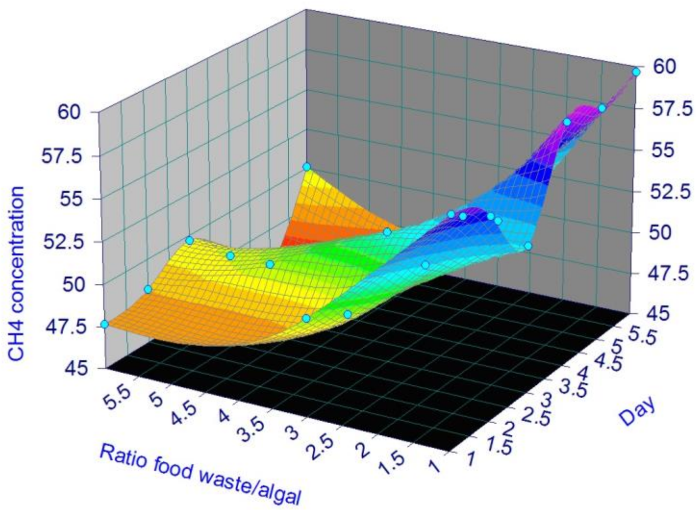
CH4 concentration
Ratio food waste/algal
Day
60
57.5
55
52.5
50
47.5
45
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1

Fig. 4

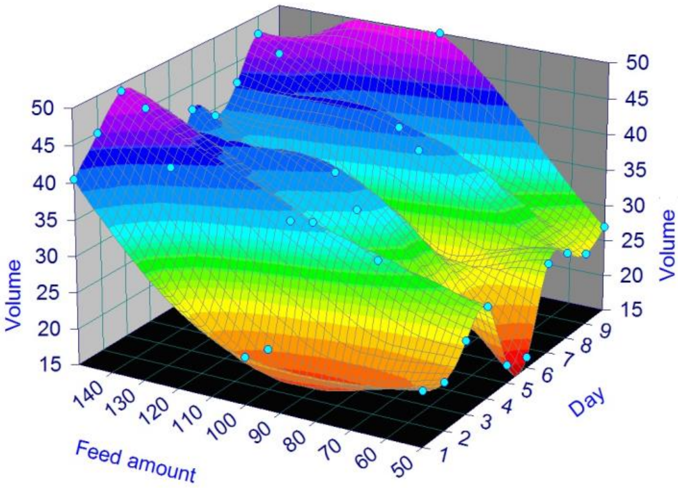

Fig. 5

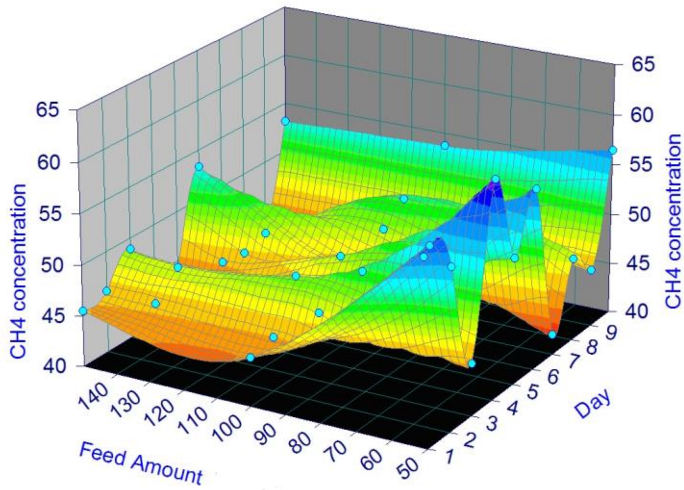

Fig. 6

5. Conclusions

It was studied AcoD of delipized microalgae biomass and a food residue (potato waste). The experimental results are encouraging for the future of renewable energy production. The modeling of this process is imposed by the search of the optimum conditions which give a maximum production of biogas. From the five categories of available mathematical models for AD and AcoD it was obtained the most ready to hand type of models, respectively statistical models. With the eqs. (1) – (4) this AcoD process can be partially simulated and optimized with satisfactory results. We intend to extend the experimental investigations using and others food residues, and others parameters such as chemical composition of the food residue, organic loading, pH, intensity of stirring, etc. The eqs. (1) – (4) will be a part of a more extended statistical model, that will be very useful for the search of maximization of biogas production.

It is imperious necessary the improving of AcoD modelling capacities to simulate the complex physicochemical and biochemical processes [7]. A new promising direction of search consists in the use of synergetic effects for the simultaneous use of several food residues [12]. Mathematical modelling of AcoD has been developed based on both empirical and mechanistic approaches. AcoD operates at high organic loading rates under diverse co-substrates' properties and composition. The transient variation in pH and inhibitory intermediates are essential for AcoD optimization [7]. New features in future AcoD models should involve interrelationships between system performance and co-substrates' properties, organic loading and inhibition mechanisms. Xie et al. [7] have presented a very useful future research roadmap for further development of AcoD modelling capacity, exposed here in Fig.7.

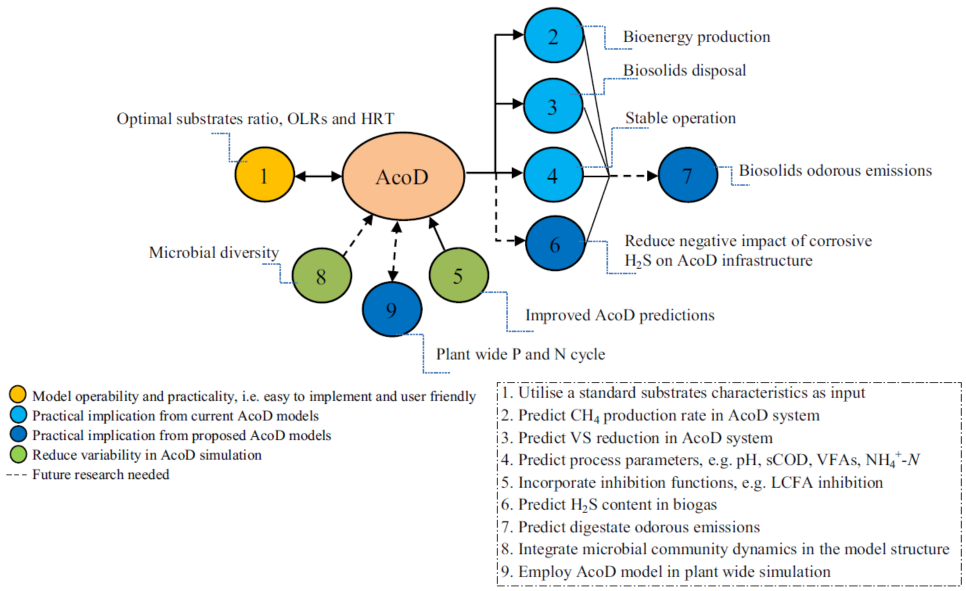

Fig. 7 Future research roadmap for further development of acod modelling capacity [7]

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